Integration of RIS into O-RAN 5G Networks and Beamforming Optimization via UE Reporting

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***Abstract*—This paper explores the integration of Reconfigurable Intelligent Surfaces (RIS) into an Open Radio Access Network (O-RAN) for 5G systems, with a focus on optimizing beamforming through User Equipment (UE) reporting. The integration method is demonstrated in a field test where RIS dynamically adjusts its beamforming configuration based on real-time feedback from the UE, specifically using Reference Signal Received Power (RSRP) data. The results show significant improvements in signal strength and throughput, validating the effectiveness of RIS in enhancing network performance without requiring modifications to existing network protocols. This work highlights the potential of RIS to improve coverage and capacity in 5G environments.**

***Index Terms*—RIS, O-RAN, mmWave, real-world performance, TRL 7, RSRP, beamforming, radio access network.**

I. Introduction

The rapid development of Reconfigurable Intelligent Surfaces (RIS) is poised to significantly impact the design of wireless networks, especially in the context of 5G and beyond. RIS technology provides a transformative approach to enhancing signal propagation, particularly in scenarios where traditional techniques fall short. RIS can serve dual roles in both communication and sensing, offering architectural flexibility across a wide range of applications. In communication, RIS can enhance network performance by improving coverage, increasing the received signal strength, and reducing interference [1, 2, 3]. On the sensing side, RIS is also capable of localizing objects and aiding in advanced positioning and tracking [4, 5].

For RIS to deliver its promised benefits in communication systems, precise beamforming is essential. To ensure maximal power delivery to the user equipment (UE), the reflected signal from the RIS must be precisely steered. However, small variations in the direction of the reflected signal can lead to a significant loss of signal strength. Consequently, beamforming must be continuously optimized to sustain optimal signal quality at the UE.

In the context of 5G and beyond, where massive connectivity and low latency are crucial, RIS optimization must be done seamlessly within the existing network infrastructure. The Open Radio Access Network (O-RAN) architecture serves as an ideal framework for this integration due to its inherent modularity and openness to third-party innovation. Specifically, for RIS to be integrated effectively into an O-RAN-based network, it is necessary to design a procedure that utilizes network protocols and the information provided by the UE, such as the Reference Signal Received Power (RSRP), to adapt the RIS beamforming dynamically.

Recent studies and field trials have demonstrated that incorporating RIS into 5G networks can significantly improve network performance [6, 7, 8], particularly in terms of coverage and signal quality. The integration of RIS into O-RAN has emerged as a promising avenue for future wireless systems, as it combines the flexibility of software-defined control with the benefits of artificial intelligence, edge computing, and virtualization. Despite this potential, RIS deployment within the O-RAN framework remains relatively unexplored [9].

This paper presents an integration method of mmWave RIS into an O-RAN 5G mmWave network, focusing on optimizing the RIS beamforming through UE reporting. The method consists of two main parts: (1) the connections and control flow and (2) the optimization procedure for RIS beamforming using network normal reporting. We conduct a field test to validate the performance improvements achieved by the RIS and demonstrate the feasibility of integrating it into the existing 5G architecture without requiring significant changes to the network protocols.

II. RIS Model

We consider an RIS composed of $M \times N$ reflecting elements arranged in a uniform planar array. Let the total number of elements be $L = MN$, and denote the position of the (m, n)-th element by $\vec{r}_{m,n} \in \mathbb{R}^3$. Let $\vec{r}_{\text{tx}} \in \mathbb{R}^3$ and $\vec{r}_{\text{rx}} \in \mathbb{R}^3$ be the spatial coordinates of the source (transmitter, Tx) and the target (receiver, Rx), respectively.

The RIS operates by introducing phase shifts to the incident electromagnetic field at each element, such that the reflected wavefront can be coherently steered toward the receiver. This model assumes line-of-sight propagation between the TX and the RIS, and between the RIS and the RX. We neglect mutual coupling between elements and model the RIS as an ideal phase-controlling surface.

The complex field incident on the (m,n)-th RIS element can be expressed as:

$$h_{m,n}^{(\text{in})} = \frac{1}{d_{m,n}^{(tx)}} e^{-jkd_{m,n}^{(tx)}}, \tag{1}$$

where $d_{m,n}^{(tx)} = \|\vec{r}_{m,n} - \vec{r}_{\text{tx}}\|$ is the distance from the transmitter to the (m,n)-th RIS element, and $k = \frac{2\pi}{\lambda}$ is the wave number.

Likewise, the propagation from the (m,n)-th RIS element to the receiver is given by:

$$g_{m,n}^{(\text{ref})} = \frac{1}{d_{m,n}^{(rx)}} e^{-jkd_{m,n}^{(rx)}}, \tag{2}$$

where $d_{m,n}^{(rx)} = \|\vec{r}_{m,n} - \vec{r}_{\text{rx}}\|$ is the distance between the RIS element and the receiver.

Each RIS element applies a reconfigurable phase shift $\phi_{m,n}$ to the incident field. In the case of 1-bit RIS (mmWave RIS from Greenerwave[1]), the phase shift is quantized to the set $\{0, \pi\}$, such that the reflection coefficient becomes:

$$b_{m,n} = e^{j\phi_{m,n}} \in \{+1, -1\} \tag{3}$$

The total field at the receiver level, can be expressed as:

$$y = \sum_{m=1}^{M} \sum_{n=1}^{N} g_{m,n}^{(\text{ref})} \cdot b_{m,n} \cdot h_{m,n}^{(\text{in})} \tag{4}$$

Substituting the expressions for $g_{m,n}^{(\text{ref})}$ and $h_{m,n}^{(\text{in})}$, the received field becomes:

$$y = \sum_{m=1}^{M} \sum_{n=1}^{N} b_{m,n} \cdot \frac{1}{d_{m,n}^{(tx)} d_{m,n}^{(rx)}} \cdot e^{-jk(d_{m,n}^{(tx)} + d_{m,n}^{(rx)})} \tag{5}$$

This expression captures the aggregate field contribution at the receiver from all the elements of the RIS, each modulated by a discrete phase shift. Optimizing the phase shift vector $\{\phi_{m,n}\}$ is essential to maximizing the received signal strength, which is the objective of the beamforming optimization procedure discussed later in the paper.

III. Methodology

A. Setup

The experimental testbed was constructed to evaluate the feasibility of integrating a RIS within a live O-RAN 5G environment. First, the experiment used an integrated Active Antenna Unit (AAU), which combines both the Radio Unit (RU) and MIMO antenna. The AAU serves as the primary access point for the radio access network.

A mmWave RIS from Greenerwave was utilized for the experiment. The RIS is capable of dynamically adjusting its configuration, and it is controlled by a RIS controller, which adjusts its configuration based on a predefined algorithm. The RIS controller can be connected to the established O-RAN network or to any other testing equipment. The main specifications for the RIS are shown in Table I.

The UE used in this test was provided by Quectel, and it is already registered to the network using a dedicated SIM. Being connected to the established network, the UE provides periodic reports of the RSRP, which is then used for optimizing the RIS beam direction.

TABLE I: The specifications of the used RIS

Parameter	**Value**
Polarization	dual, H-pol and V-pol
Operating frequency	27 GHz
Operating Bandwidth	2 GHz
Half power beam width	3-5 degree (controllable)
Scan Range (Azimuth, Elevation)	+/- 60 deg.
Beamforming capabilities	Variable beamwidth Multibeaming
Active area size	200 mm x 200 mm

The setup took place at EURECOM campus in Sophia, France. The AAU was placed in a corridor in the office floor, aligned with the existing infrastructure, to provide a controlled yet representative network environment. The UE was deliberately positioned in a Non-Line-of-Sight (NLoS) location relative to the AAU to emulate challenging propagation conditions and assess the RIS's ability to compensate for link degradation. The RIS was deployed in a Line-of-Sight (LoS) position with respect to the AAU and within effective reflective range of the UE, enabling efficient signal redirection. Figure 1 shows the setup plan (1a) and the placement of the components at the location (1b).

B. Software Tools

To achieve adaptive beamforming and seamlessly integrate the RIS into the O-RAN architecture, several software tools were developed and utilized within the RIS controller. The controller uses an algorithm that calculates the configuration of the RIS based on the incident and reflected angles of the signals.

In addition, an API was developed for controlling the RIS in real-time. This API allows the RIS controller to dynamically adjust the configuration of the RIS. Another API enables the RIS controller to access the network broker, which ,among other things, retrieves RSRP data from the UE.

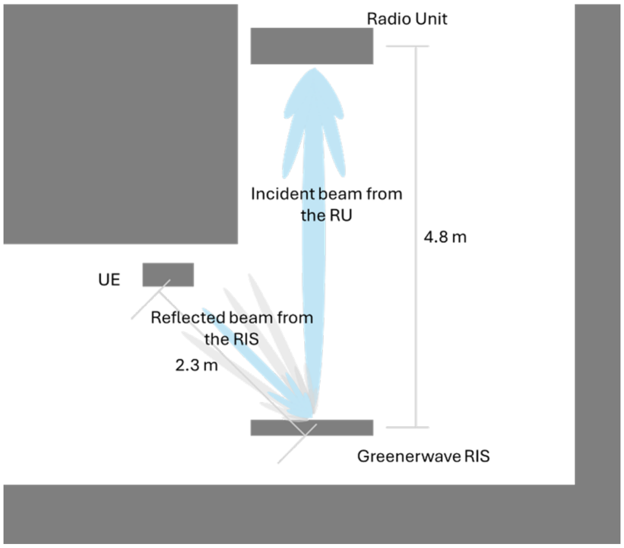
Moreover, a procedure was implemented to search for and localize the UE within the network. This procedure allows the RIS to adjust its beamforming dynamically to enhance signal strength using the APIs and the algorithm mentioned earlier. The details of the procedure are the subject of the next section.

IV. Proposed Procedure

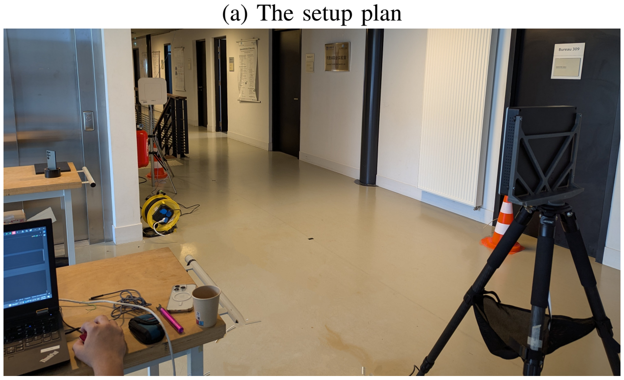
A. Network Integration

1) Connection setup: The integration of the RIS into the O-RAN 5G network is implemented following the configuration shown in Figure 2. The Active Antenna Unit (AAU) is connected to the Distributed Unit (DU) via a high-speed fronthaul fiber link, following the eCPRI standard. The AAU acts as the radio head for the cell, interfacing directly with the User Equipment (UE), which is registered in the network via a dedicated SIM card.

The RIS controller is connected to the network over Ethernet and is logically integrated with the system via an API exposed



(a) The setup plan



(b) The setup location

Fig. 1: The testing setup

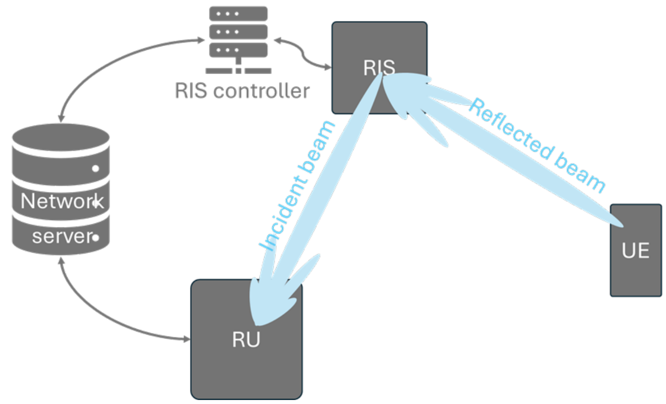


Fig. 2: The connection scheme of the components of the integrated system

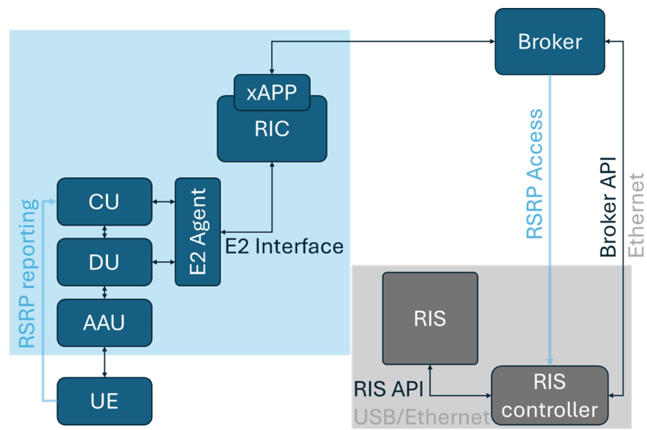


Fig. 3: The flow of control information through the components of the network for RIS integration

by a software module referred to as the broker. This broker, hosted on the network server, provides access to UE radio measurements, particularly the RSRP, and serves as a data abstraction layer. The RIS controller is also connected to the RIS hardware via USB or Ethernet, depending on the deployment. Functionally, the controller operates as a network-aware node capable of querying real-time performance metrics and adjusting RIS configurations accordingly.

2) Control Flow: The control flow within the network is designed to facilitate seamless communication between the UE, the RIS controller, and the network components. The UE periodically sends RSRP reports to the CU. This RSRP data is then forwarded to the RAN Intelligent Controller (RIC) through an E2 agent. The RIC uses an xApp to grant access to the RSRP data, which is pulled by the broker when required.

The RIS controller requests the RSRP data through the broker when it is needed. It adjusts the RIS configuration to optimize beamforming and improve the signal quality based on that information as a main feedback. The RIS continuously adjusts its configuration in real-time to ensure that the reflected signal is directed towards the UE with the best possible alignment, thereby maximizing signal strength. The control flow is shown in Figure. 3.

B. Optimization procedure

To optimize the beamforming configuration of the RIS, we employ a sequential exhaustive search algorithm that dynamically evaluates and selects the most favorable beam configuration based on the RSRP.

The procedure begins by verifying the initialization state of the RIS. If the RIS is not yet initiated, the system activates it before proceeding. Once the RIS is operational, the algorithm defines the boundaries of the search space—specifying the candidate beams to be evaluated. The search boundaries start from an initial estimation of the general direction of the UE with respect to the RIS. It can be obtained by the previous known location. The search boundaries define how wide the search would be, and the angular step size between beams in that search.

The core of the procedure consists of an iterative loop that cycles through each candidate beam. For each iteration, the RIS is configured to reflect the n^{th} beam, after which the system measures the RSRP. The obtained RSRP is then compared against the best recorded value. If the new measurement exceeds the current optimal RSRP, the system updates the stored optimal beam configuration accordingly. The index is incremented, and the process continues until all N candidate beams have been evaluated.

Upon completion of the search, the beam configuration corresponding to the highest recorded RSRP is selected and returned as the optimal beam direction. This procedure ensures that the RIS adaptively aligns its reflection characteristics to maximize signal strength at the receiver, enhancing the overall performance of the 5G communication link. The procedure is summarized in Figure. 4 and in Algorithm 1.

Algorithm 1 Beamforming Optimization

Require: x_{Tx}, y_{Tx}, z_{Tx}, θ_{Rx}, ϕ_{Rx}, M, $step_{Tx}, step_{Rx}$: Tx/Rx position search range
Ensure: best RIS configuration
initiate RIS
initial power ← -100
best RIS configuration ← zeros
for $i = 1$ to M **do**
  RIS configuration[i] = f(x_{Tx}, y_{Tx}, z_{Tx}, θ_{Rx}, ϕ_{Rx})
  Load RIS configuration[i] to RIS
  delay (150ms)
  power ← $RSRP_{UE}$
  if power > initial power **then**
    initial power ← power
    best RIS configuration ← RIS configuration[i]
  end if
  update x_{Tx}, y_{Tx}, z_{Tx}, θ_{Rx}, ϕ_{Rx} ▷ based on $step_{Tx}, step_{Rx}$
end for
Load best RIS configuration to RIS
return best RIS configuration

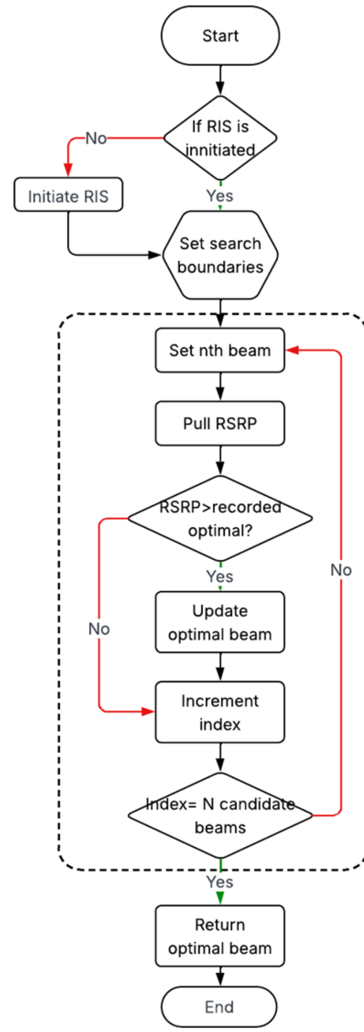


Fig. 4: RIS beamforming optimization procedure

V. Testing and Results

To validate both the RIS performance and the integration scheme, two phases of testing were conducted. In the first phase, a reference optimization using lab equipment is performed. In the second, the optimization is done through the network integration.

A. Phase One: RIS validation

The first phase of testing was focused on validating the performance of the RIS in enhancing the received signal at the UE. The goal was to provide a benchmark for the subsequent testing phase, as well as to assess the improvements in signal quality resulting from RIS optimization.

The testing setup for this phase involved the following components:

- A directive antenna was placed at the same location as that of the UE, connected to a portable Spectrum Analyzer (SA) to measure the received power.
- The Spectrum Analyzer was then connected to the RIS controller to record the signal measurements.
- The rest of the setup remained the same as described earlier, with the RIS, AAU, and UE positioned according to the deployment plan.

In this setup, the spectrum analyzer provides the necessary feedback for the active optimization of the RIS beamforming. While operating a similar procedure as the one described in IV-B, the feedback provided by the network is substituted by a power measurement from the SA, facilitated by an API.

Once the optimization is completed, the RIS configuration is set to the optimal set, and the received RSRP and reported data rate are recorded. the RIS is then turned off, and the RSRP and the data rate are recorded again as a reference. The reported RSRP with and without the RIS are shown in Fig. 5 and the report data rate is shown in Fig. 6.

This phase demonstrated that the RIS could provide significant gain in received power when optimized. Specifically, the RIS provided a gain of 8 dB in RSRP, moving the average received RSRP from -52.2 dBm to -44 dBm. Additionally, the average throughput improved by 25.7% as a result of the RIS beamforming optimization. In addition, results indicate a significant reduction in signal and throughput variability when RIS is active. The standard deviation of the RSRP dropped from 0.6 dB to almost 0 dB, and that of the throughput dropped from 11.6 to 0.4 Mbps.

B. Phase Two: Validation of the RIS integration

Phase Two focused on validating the RIS integration into the O-RAN network and testing the optimization procedure in

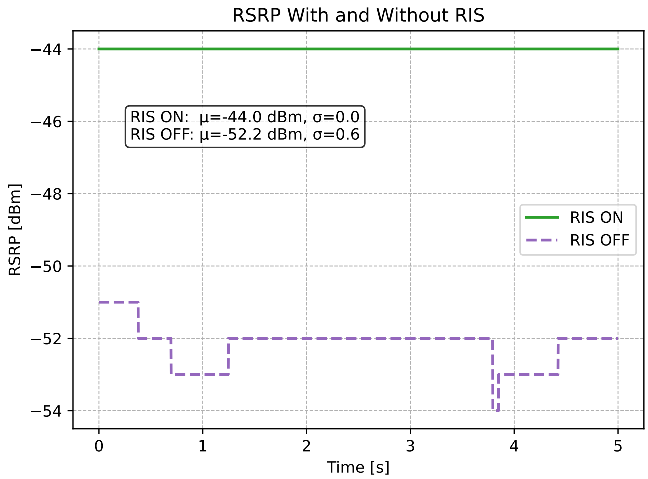


Fig. 5: RSRP comparison with SA

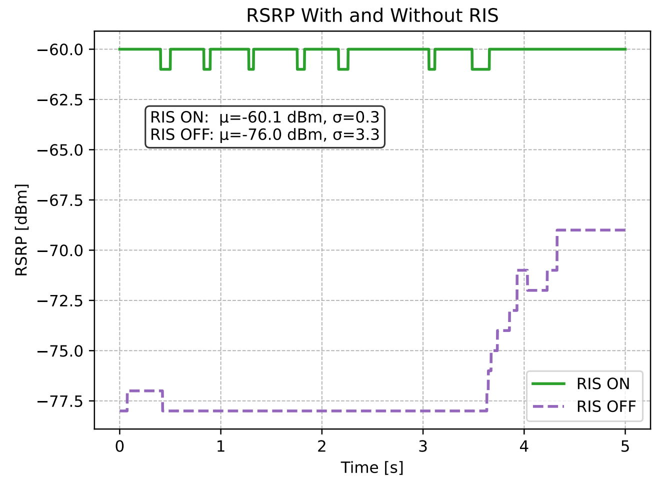


Fig. 7: RSRP comparison with O-RAN

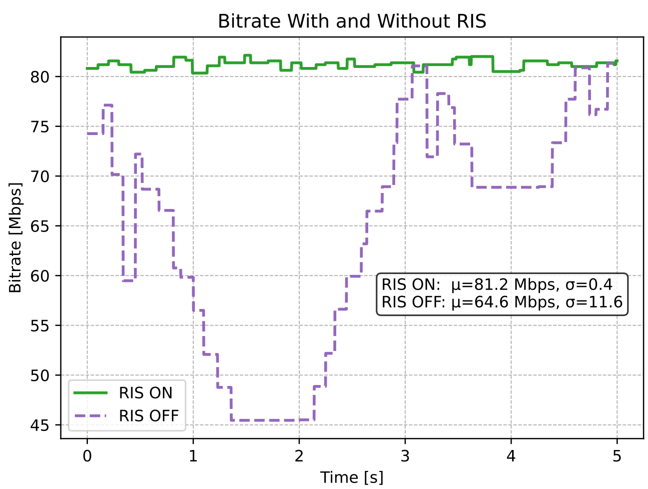


Fig. 6: Bit Rate comparison with SA

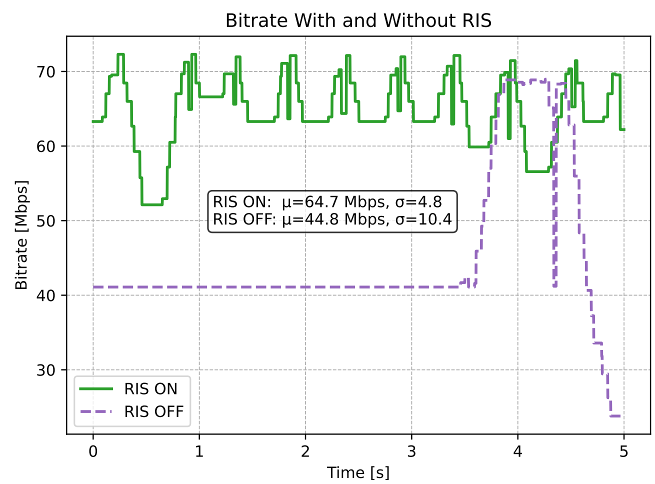


Fig. 8: Bit Rate comparison with O-RAN

a real network environment. The goal was to ensure that the RIS could be effectively controlled via network protocols and optimize its beamforming based on real-time UE feedback.

In this phase, the Quectel UE was placed at its designated location and attached to the network. the distance between RIS and the UE is increased for more realistic testing environment. The RIS control was connected only to the network, and the setup remained the same as in Phase One.

The procedure for Phase Two began with the operation of the AAU, followed by recording the RSRP reported by the UE to the network, which was used as the baseline measurement. After establishing the baseline, the configuration of the RIS was adjusted based on the procedure detailed in IV-B. The optimal reflection angle was then selected based on the highest recorded RSRP. The RIS was then set to this optimal configuration, and the RSRP and throughput data were collected for a specified duration to assess the ongoing performance. To complete the procedure. A post-optimization baseline was recorded with the RIS deactivated to quantify relative gain. The reported RSRP with and without the RIS are shown in figure 7 and the report data rate is shown in 8.

Phase Two confirmed the successful integration of the RIS into the O-RAN network. The RIS was able to optimize its beamforming in real-time based on the RSRP feedback from the UE. The RIS provided a gain of 16 dB in RSRP, increasing it from -76 dBm to -60.1 dBm. The RIS beamforming lead also to a 44.4% increase in throughput. Similar to the 1st stage, the RIS reduced the fluctuation in the received power and the data rate, reducing their respective standard deviation by 3 dBm and 5.6 Mbps.

It is important to note that the optimization duration was found to depend on the reporting frequency of the RSRP and the range of angles to search through.

VI. Conclusions

This paper presented the integration of Reconfigurable Intelligent Surfaces into an O-RAN 5G network, focusing on optimizing RIS beamforming through User Equipment reporting. The study demonstrated the successful deployment and integration of RIS into a real-world 5G network, and the results of a field test were discussed in detail. The RIS showed significant potential in enhancing the received signal quality by optimizing the beamforming direction.

The integration of RIS into the O-RAN network was seamless, and the RIS controller was able to adjust the RIS configuration in real-time based on the feedback from the UE, specifically the RSRP. The optimization process led to a substantial gain in signal quality. Specifically, the RIS provided a gain of 16 dB in RSRP resulting in a 44.4% increase in throughput. These improvements validate the effectiveness of RIS for optimizing network performance in 5G environments.

The integration was performed without adding significant overhead to the network, and without changing existing protocols and procedures. the proposed protocol can be implemented in any deployment with minimal effort, which facilitates the integration.

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REFERENCES

[1] Jean-Baptiste Gros et al. "Design of reconfigurable intelligent surfaces at mmwave with application to 5g/6g". In: *2023 17th European Conference on Antennas and Propagation (EuCAP)*. IEEE. 2023, pp. 1–4.

[2] Ahmad Shokair et al. "Real World Field Trial for RIS-Aided Commercial 5G mmWave Wireless Communication". In: *2024 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*. IEEE. 2024, pp. 576–581.

[3] Wankai Tang et al. "Wireless communications with reconfigurable intelligent surface: Path loss modeling and experimental measurement". In: *IEEE transactions on wireless communications* 20.1 (2020), pp. 421–439.

[4] Anum Umer et al. "Reconfigurable Intelligent Surfaces in 6G Radio Localization: A Survey of Recent Developments, Opportunities, and Challenges". In: *IEEE Communications Surveys & Tutorials* (2025).

[5] Hui Chen et al. "6G localization and sensing in the near field: Features, opportunities, and challenges". In: *IEEE Wireless Communications* (2024).

[6] Jian Sang et al. "Coverage enhancement by deploying RIS in 5G commercial mobile networks: Field trials". In: *IEEE Wireless Communications* 31.1 (2022), pp. 172–180.

[7] Ruiqi Liu et al. "Simulation and field trial results of reconfigurable intelligent surfaces in 5G networks". In: *IEEE access* 10 (2022), pp. 122786–122795.

[8] Sefa Kayraklık et al. "Indoor coverage enhancement for RIS-assisted communication systems: Practical measurements and efficient grouping". In: *ICC 2023-IEEE International Conference on Communications*. IEEE. 2023, pp. 485–490.

[9] Kostas Katsalis et al. "RIS Technology Integration with the 5G System: Challenges and Open Questions". In: *2024 IEEE Conference on Standards for Communications and Networking (CSCN)*. IEEE. 2024, pp. 14–19.